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An investigation of the positive point streamer corona

Part I. The time distribution of the streamers

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With 21 figures in the text

SUMMARY

The self-sustaining positive point streamer corona discharge is of special interest because it can be used as a fast hygrometer [1, 2]. The behaviour of the positive point streamer discharge has been studied by Loeb *et al.* [3–14]. However, as they used hemispherical points they could only study so-called pre-onset streamers and did not observe any streamers in the self-sustaining discharge. In this investigation conical points are used and streamers are obtained in the self-sustaining discharge.

The time distribution of the streamers is measured and it is found that after a streamer has been formed, there is a dead time t_0 during which no new streamer can be formed. A number of experiments are carried out which show that the dead time is caused by negative ions formed in the preceding streamer.

Introduction

In earlier papers [1, 2] it has been shown that the so-called combined continuous and streamer corona can be used as a fast hygrometer. This type of self-sustaining corona discharge is observed if a point-to-plane setup (positive point) is used, the point having a suitable shape. As the combined continuous and streamer corona has practical applications, it is of especial interest to study its behaviour. The streamer formation has been studied for about 20 years [3–15], but almost all this work has been done with hemispherical points. As a consequence only so-called pre-onset streamers have been observed and studied. No streamers appear after onset of the self-sustaining corona discharge when this point shape is used. It is necessary to use a potential lower than the threshold of the self-sustaining discharge and to ionize the gas in the corona gap by a radioactive sample. When such a source of ionization is used, the chance of streamer formation is not constant from time to time. The ionization takes place in a random way, and a thorough investigation of the streamer formation is impossible in some respects. The discharge used here is self-sustaining, and no radioactive sample has been used to ionize the gas.

The first investigations of the pre-onset streamers were made by Loeb and co-workers [3] by using a point-to-plane arrangement. Pioneering work on the discharge was carried out by Kip [4] and Trichel [6] who found that the streamers are formed in a very short time (less than 10^{-7} sec). Other investigators [7, 8, 9, 10] noted that the streamer formation is dependent on the humidity of the air and on admixtures of other gases, for instance CO_2 and freon. A thorough study of the discharge has been made by Amin [12] who has used modern techniques to measure the speed of advance of the streamer tip, among other things. Streamer formation has also been studied with coaxial cylinders; the latest investigation with this arrangement was made by Huber [14].

1. Description of the discharge

The simplest way to get a discharge of the type investigated in this work is shown in Fig. 1*a*. A platinum point S is placed at a distance of 2–5 mm from the metal plane P. The point is connected via a resistance, R_1, to a stabilized high tension source which can supply at least 4000 volts. The point is made positive. The plane is grounded via a resistance, R_2. The resistance R_1 has a very small influence on the discharge and may be omitted.

The corona point S is made of a 0.3 mm platinum wire in the shape of a cone with a half angle of about 45°. This angle has proved to be the most suitable, but the same type of discharge is obtained if the half angle is made somewhat smaller, for instance 35°, or somewhat larger, for instance 55°. After the discharge has been burning for some time, the point becomes somewhat rounded at the tip as shown in Fig. 2; any further alteration has not been observed. Fig. 2 shows the shape of the point used in this work.

It is of great importance that the discharge does not change with time. In order to prevent any alteration it has proved necessary to drill a hole, H (Fig. 1*a*) in the plane P opposite to the point. If no hole is drilled in the plane, an insulating oxide layer is formed on the metal surface opposite to the point. Electrostatical charges on this oxide layer affect the electrical field in front of the point and the discharge changes.

The geometrical shape of the electrode P is in other respects of small importance. The plane can be replaced by a tube (diam. 2 cm) having the wire running along its axis (Fig. 1*b*). This arrangement has been used in some experiments.

A photograph of the discharge is shown in Fig. 3. At the top of the photograph one sees the outline of the conical point. This is surrounded by a luminous layer of 0.01–0.03 mm thickness. This layer constitutes the so-called continuous discharge. This has been so designated because it burns continuously without any interruptions.

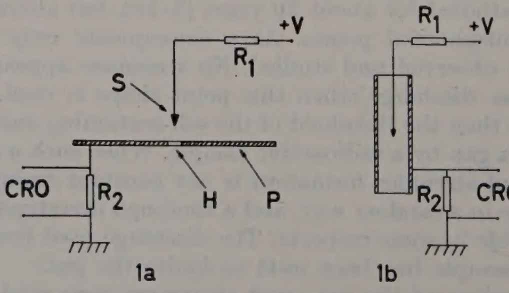

Fig. 1. The simplest way to get a discharge of the type studied in this investigation. Streamers are formed at the platinum point S. The shape of the cathode is of rather small importance. In *a* a plane is used and in *b* a tube. In order to avoid the formation of insulating oxide layers on the cathode a hole H has been drilled in the plane. Cathode-ray oscilloscope is abbreviated CRO.

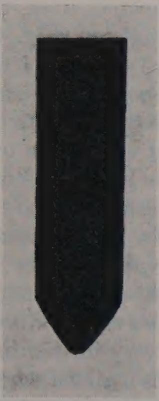

Fig. 2. The shape of the point at which the streamers are formed. The point is made of platinum wire, 0.3 mm diameter.

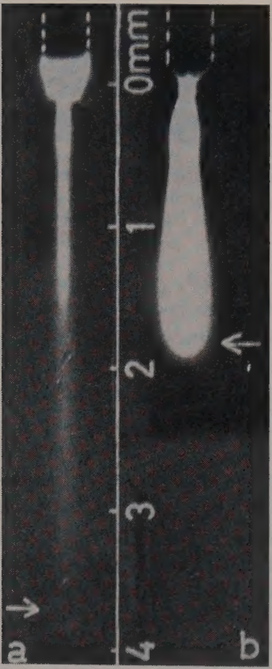

Fig. 3. Photograph of the discharge (atmospheric pressure, room temperature). Relative humidity: *a*, 30 %; *b*, 100 %. Time of exposure: *a*, 2 hours; *b*, 15 minutes.

The point voltage is accordingly equal to or greater than that which is necessary for the self-sustaining discharge.

In the continuous discharge adjacent to the point new electrons, positive ions and photons are continuously formed. The electrons and photons are able to ionize the gas, whereas the ionizing power of the positive ions is very small. The positive ions have a large mass and move very slowly compared to the electrons. The electrons move rapidly towards the point, and the positive ions are left behind forming a positive space charge. As all the processes in the discharge are subject to statistical fluctuations, this must also be the case with the positive space charge.

Apart from the continuous discharge adjacent to the point Fig. 3*a* shows a luminous brushlike space, which starts at the point and extends about 4 mm towards the plane. This is the visual appearance of the streamer discharge. It is to be noted that this is not the picture of one streamer but of many thousands of superimposed streamers. A streamer (in the notation used in this paper) is a narrow, threadlike discharge that starts at the point and advances out into the gap. In the case shown in Fig. 3*a* (atmospheric pressure, room temperature, 30 % relative humidity) the streamer is about 4 mm long. It has probably a cylindrical shape and its diameter seems to be less than 0.05 mm. As mentioned above, the time of formation is very short, and the streamers propagate out into the gap with a velocity of more than 10^7 cm/sec [12]. When a streamer is formed, it gives rise to a rapid potential variation in the

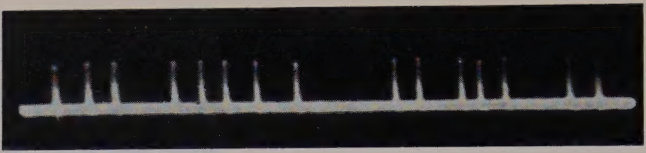

Fig. 4. A photograph of one sweep on the oscilloscope screen. Each time a streamer is formed the potential over the resistance R_2 (Fig. 1) suddenly increases. The shortest time interval between two pulses is about 100 microseconds.

electrical circuit. If a cathode-ray oscilloscope is connected over the resistance R_2, a pulse is seen on the screen every time a streamer is formed (Fig. 4, one sweep). The shortest time interval between two pulses is in this case about 100 μsec.

The streamer theory of the spark was proposed by Raether [16] in connection with his cloud-chamber experiments on breakdown. The same theory was used by Loeb and Meek [17] to explain the mechanism of the pre-onset streamers in the positive point corona. According to this theory the electrical field is hihgly distorted owing to a positive ion space charge at the head of the streamer. Electrons are generated in the gap by the intense photo-ionization in the gas caused by the photons produced in the electron avalanches. These electrons initiate new avalanches in the distorted field. As the velocity of the electrons is about 10^2 times that of the ions, the electrons rapidly proceed from the place where they are produced, leaving behind the positive ions that distort the field. The streamer advances in this way in the direction of the applied electrical field, and it does not stop until it reaches a space where this field is too weak for the streamer to propagate. The condition for the formation of the first part of the corona streamer seems, however, to be much more complex than for the propagation of the streamer after this first part has been formed.

2. The properties of the discharge

The properties of the combined continuous and streamer discharge are determined mainly by three factors:

(1) the shape of the point,
(2) the voltage difference between the point and the plane,
(3) the nature and the pressure of the gas.

There is not much to say about the shape of the point. It must not deviate too much from the normal shape described above (a cone with a half angle of 45°). If the point is made too sharp, only the continuous corona discharge appears and no streamers are formed. If it is too blunt, one approaches the case described in the introduction, and streamers are formed only at a voltage lower than the onset voltage of the self-sustaining discharge. In this case streamers appear only if the gas in the gap is ionized by, for instance, a radioactive sample.

The effect of the point voltage on the streamer formation is shown in Fig. 5. The number of streamers formed per second, n, is shown as a function of the point voltage V. The gas used is air at atmospheric pressure, and measurements have been made at 30, 50, 75, and 100 % relative humidity (room temperature). If V is less than V_0 (V_0 = onset voltage), a self-sustaining discharge is not possible and consequently $n = 0$. If a radioactive sample is used to ionize the gas, streamers are formed even if the potential of the point is somewhat lower than the onset voltage V_0. If V is

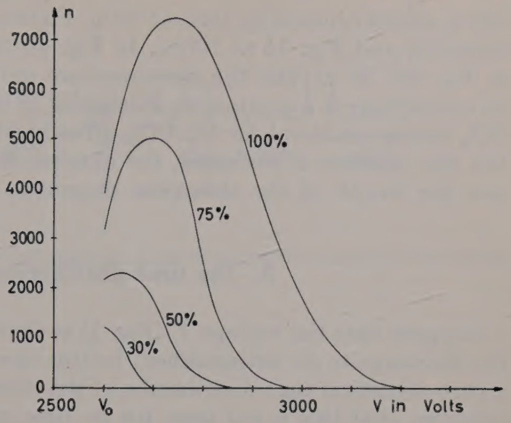

Fig. 5. The number of streamers formed per second as a function of the point voltage V. Air at atmospheric pressure and 30, 50, 75, and 100 % relative humidity (room temperature). V_0 is the onset voltage.

greater than V_0, n increases at first, reaches a maximum and then decreases slowly to zero. Streamers are formed only within a definite voltage interval that is dependent on the shape of the point and the nature of the gas. If the gas employed is air at atmospheric pressure and 30 % relative humidity, the interval is about 100 volts. If the relative humidity of the air is increased, the interval increases. If a mixture of nitrogen and oxygen is used (more than about 50 % oxygen), streamers appear during the whole voltage interval between onset and breakdown.

Both the number of streamers formed per second and the length of the streamers depend on the composition of the gas in the corona gap. Thus in a mixture of air and water vapour, more streamers are formed the higher the percentage of water vapour. At a voltage of about 100 volts above onset, the number of streamers formed per second is about 50 at 30 % relative humidity (room temperature) and about 7000 at 100 %. Admixtures of small amounts of, for instance CO_2, SO_2, CCl_4 cause a considerable increase in the number of streamers formed per second. An increase in the amount of oxygen in the air has a similar effect. In oxygen about 70000 streamers are formed per second. If, on the other hand, the amount of oxygen in the $N_2 + O_2$ mixture is less than about 35 %, no streamers are formed at all.

No streamers have been observed in A, H_2, N_2, CO_2, $N_2 + H_2$ mixtures and $N_2 + CO_2$ mixtures. On the other hand, streamers are formed in N_2 with an admixture of small amounts of A, HCl, Cl_2, freon or CCl_4, in $N_2 + H_2$ mixtures with small amounts of A, and in $N_2 + NH_3$ mixtures with more than about 10 % NH_3. As mentioned above, streamers are formed in $N_2 + O_2$ mixtures with more than about 35 % oxygen.

During our work on the streamer discharge we wanted to investigate the influence of the negative ions on the streamer formation. Therefore measurements have been made in mixtures of nitrogen and another gas, for instance in $N_2 + O_2$ mixtures, N_2 + freon mixtures and N_2 + A mixtures [29]. The reason for this is that no negative ions are formed in nitrogen by attachment of electrons. Of course no negative ions are formed in argon, but in many respects there are great differences between this monoatomic gas and the other gases used here. Nitrogen is consequently preferable to argon.

If the admixture of a gas increases the number of streamers formed per second, the length of the streamers generally decreases. An example of this is shown in Fig. 3. As mentioned above (see Fig. 5), more streamers are formed per second in air at

100 % relative humidity than at 30 %. Figure 3*a* shows the discharge at 30 % relative humidity and Fig. 3*b* at 100 %. In Fig. 3*a* the streamers are about twice as long as in Fig. 3*b*. In oxygen the streamers are only about 0.5 mm long and in $N_2 + CCl_4$ mixtures there is a continuous shortening of the streamers from about 4 mm at 10^{-3} % CCl_4 to zero at about 10^{-1} % CCl_4. Finally, if the composition of the gas is constant but the pressure is increased, the number of streamers formed per second increases and the length of the streamers decreases.

3. The time distribution of the streamers

Suppose that the voltage V (Fig. 1) is chosen so high that there is no tendency for the discharge to be extinguished. In this case it is reasonable to expect that there is a pure statistical time distribution of the streamers. If one looks at Fig. 4 it is evident, however, that this is not true, for no time interval is less than about 100 μsec. The appearance of a "dead time"—that is, a time during which no streamers are formed—is well known to the investigators of the pre-onset streamers. An explanation of this dead time has been given in several papers [4, 5, 11, 12, 14]. It is supposed that no streamer is able to develop until the positive space charge of the preceding streamer is removed and the necessary field for streamer propagation restored.

In the discharge used in this work there is no variable radioactive ionization affecting the streamer formation. As in this case the development of streamers is determined by the discharge itself, one can expect that the knowledge of the time distribution of the streamers will be valuable for the explanation of the mechanism of the discharge.

The time analyses have been made with the electronic circuit shown in Fig. 6. When a streamer is formed, a voltage pulse appears over the resistance R_2 (Fig. 1). The pulses are amplified and fed to the Schmitt-trigger (Fig. 6). The grid of tube A normally has so low a potential that the tube is nonconducting and the capacitor C is charged through the resistance R. When a streamer is formed the Schmitt-trigger gives a positive voltage pulse which is fed to the grid of tube A. During a time of some microseconds the capacitor C is discharged through the tube A, and as soon as the pulse is over the charging process begins again. But the capacitor cannot discharge completely during a time of some microseconds. If no precautions were taken, the capacitor would be discharged to a potential that varied from time to time. The diode B controls the potential of the capacitor C so that it is always the same when the charging process begins.

If the resistance R is suitable, the potential of C just before the discharge of the capacitor is dependent on the length of the time interval between two pulses. The time variations have been transformed into amplitude variations. Tube D is simply a cathode follower placed between the high-ohmic RC-circuit and the following low-ohmic circuit with the diode E. For every time interval that is longer than a certain value determined by the circuit, the Schmitt-trigger to the right is released and the number of pulses per second is counted by the counting rate meter. This means that one counts all time intervals that are longer than a certain value, which can be varied by varying R. The circuit is calibrated with the aid of an oscillator.

The result obtained by the measurement is shown in Fig. 7 (air at atmospheric pressure and room temperature). The number of time intervals per second that have a length between t and $t + \Delta t$ is plotted (logarithmic scale) as a function of the

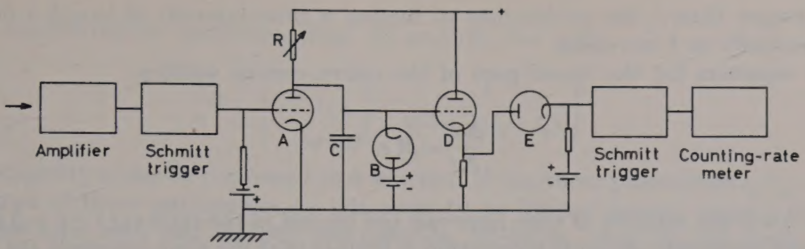

Fig. 6. The electronic circuit that has been used for measuring the time distribution of the streamers.

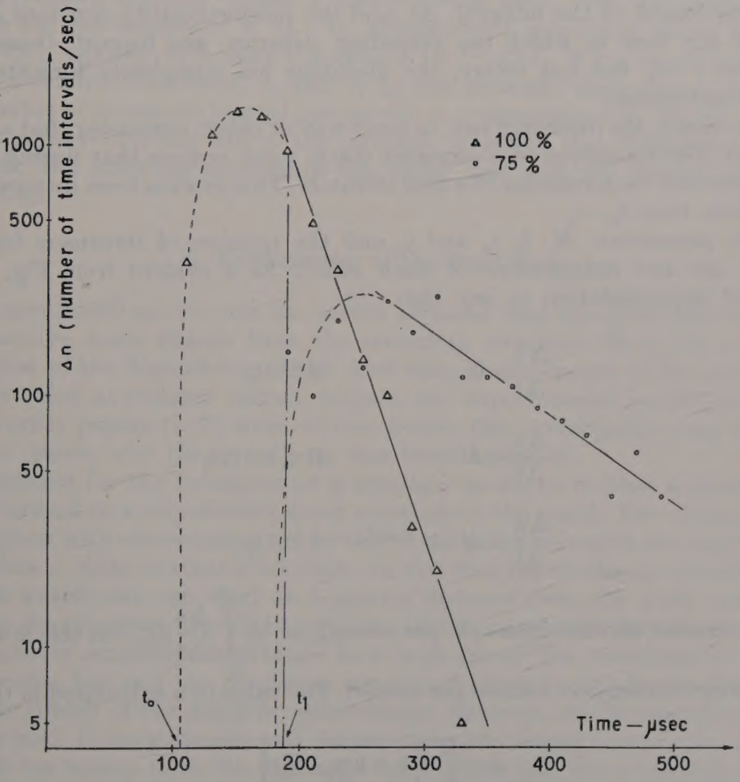

Fig. 7. The time distribution of the streamers at atmospheric pressure, room temperature and 75 and 100 % relative humidity. The dead time t_0 and the time t_1 are shown for 100 % relative humidity.

length of the time interval. Δt has been chosen equal to 20 μsec. The values that are represented by a triangle are obtained in air at 100 % relative humidity and those that are represented by a circle in air at 75 % relative humidity. From the diagram it is clear that after a streamer is formed, there is a dead time, t_0, during which the probability of streamer formation is equal to zero. After this dead time there follows a time interval, t_0—t_1, during which the probability of streamer formation is high.

For t longer than t_1 the probability of finding a time interval of length t decreases exponentially as t increases.

The equation for the linear part of the curve can be written

$$\frac{\Delta n}{\Delta t} = M e^{-k(t-t_1)}, \tag{1}$$

where Δn is the number of time intervals per second in the interval t—$t + \Delta t$, and M and k are constants. From this equation it is clear that the time intervals are statistically distributed if $t > t_1$. This means that if no streamer has been formed during the time t the chance of a streamer being formed in the time interval t—$t + \Delta t$ is proportional to the length of the interval, Δt, and the proportionality constant k is independent of the time at which the preceding streamer was formed. Consequently, after a time $t = t_1$, but not before, the discharge has completely forgotten that a streamer was formed.

During a time t_1 the discharge can, in some way or other, remember that a streamer was formed. The formation of a streamer starts some process that during a time t_0 is able to prevent the formation of a new streamer. This process loses its power during the transition time t_0—t_1.

The four parameters M, k, t_0 and t_1 and the number of streamers formed per second, n, are not independent of each other. As is evident from Fig. 7, it is a rather good approximation to say that

$$\frac{\Delta n}{\Delta t} = 0 \qquad \text{if } t < t_0,$$

$$\frac{\Delta n}{\Delta t} = M \qquad \text{if } t_0 \leqslant t \leqslant t_1,$$

$$\frac{\Delta n}{\Delta t} = M \cdot e^{-k(t-t_1)} \quad \text{if } t > t_1.$$

The total number of time intervals per second, n, is $\int\limits_0^\infty \frac{\Delta n}{\Delta t}\,dt$, but this is also equal to the number of streamers formed per second. The value of n calculated in this way is

$$n = \frac{M}{k}\left[1 + k(t_1 - t_0)\right]. \tag{2}$$

Another equation can be obtained by summing up the length of the n time intervals. The sum must be equal to 1 second. Thus

$$1 = \int\limits_{t_0}^{t_1} M \cdot t \cdot dt + \int\limits_{t_1}^{\infty} M \cdot t \cdot e^{-k(t-t_1)} dt,$$

which gives

$$1 = \frac{M(t_1^2 - t_0^2)}{2} + \frac{M}{k} t_1 + \frac{M}{k^2}. \tag{3}$$

If M is eliminated by combining Eqs. (2) and (3), one gets

$$\frac{1}{n}=\frac{1}{2}\left[t_1+t_0+\frac{1}{k}+\frac{1}{k[1+k(t_1-t_0)]}\right]. \tag{4}$$

Consequently n can be expressed as a function of the three parameters t_0, t_1, and k. The values of these parameters do not seem to be limited in any respect, but all values between zero and infinity are possible. However, they do not seem to be quite independent of each other. If t_0 is small (less than 100 μsec), k is generally large and (t_1-t_0) small—that is, t_1 is approximately equal to t_0. In this case $1/n \approx t_0$ and the streamers are very regularly distributed in time. This, for instance, is the case when the gas consists of a $N_2 + O_2$ mixture with more than about 75 % O_2 or of a $N_2 + CCl_4$ mixture with more than about 10^{-2} % CCl_4. If k is small (for instance, air at 30 % relative humidity), t_0 and (t_1-t_0) are generally large and n is small.

The number of streamers formed per second, n, is determined by Eq. (4). Of course the equation says nothing about the physical processes that determine the three parameters. The following sections of this paper deal with the process causing the dead time t_0.

4. Explanation of the dead time

As was mentioned above, one has earlier assumed that the dead time was caused by the positive space charge from the preceding streamer. However, a thorough investigation of the dependence of the dead time on the length of the streamer has shown that this hypothesis cannot explain the experimental results (see below). The two earlier papers [1, 2] were written before this investigation was made, and this is the reason why the hypothesis was there accepted.

The condition for the formation of a streamer seems to be that a positive space charge is formed in a *very limited* space adjacent to the point. This assumption can simply explain why no streamers are formed if the point voltage is too high (compare Fig. 5)—that is, if the current is too high. In this case the discharge spreads over the point. The avalanches can start at a greater distance from the point surface, and in addition they increase rapidly in number. All this causes the positive space charge to become more smoothly distributed in a large space. The variations of the space charge become less and the condition mentioned above is less frequently fulfilled.

A similar spread of the positive space charge, however, can be caused by another process as well. If negative ions and electrons are introduced into the corona gap by some other ion source than the discharge itself, these will move towards the point. They collide with a large number of gas molecules and consequently when they reach the point, they have spread over its entire surface. This results in a fairly smooth distribution of the ionization in front of the point. This process prevents the formation of localized space charges. Thus it is to be expected that negative ions and electrons reaching the point in this way will obstruct the streamer formation.

When a streamer develops, a large number of free electrons are formed in the filamentary ionization space of the streamer. These electrons move rapidly and reach the point within a time of the order of a microsecond, so that they cannot explain the dead time. However, when the electrons move towards the point, they collide with gas molecules (the mean free path is about 10^{-5} cm at 760 mm Hg); a large number of these electrons become attached to the molecules, thus forming

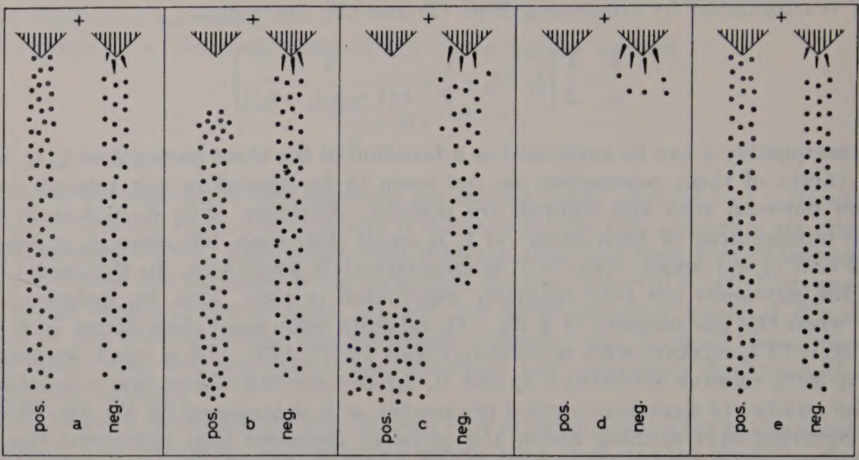

Fig. 8. The space charge distribution of positive and negative ions at different times after the formation of a streamer.

negative ions. The negative ions move considerably more slowly than the electrons. The ions formed furthest from the point reach it after a time that is of the same order of magnitude as the dead time.

The course now described is illustrated in Fig. 8, which shows the process at five different times. In Fig. 8*a* the streamer has just been formed, and both positive and negative ions are distributed over the whole length of the streamer. In Fig. 8*b* the positive ions have left the space nearest to the point, while the negative ions have moved towards the point. Fig. 8*c* shows the situation about fifty microseconds later. When the negative ions reach the high field in front of the point, they probably split into neutral particles and electrons. The latter start avalanches, and the process results in a rather uniform ionization over a large part of the point. As long as the negative ions formed in the streamer arrive at the point, it is to be expected that a new streamer cannot be formed. In Fig. 8*d* almost all the negative ions have reached the point and a new streamer can be formed. In Fig. 8*e* the new streamer has been formed.

5. Experimental verification of the theory

In order to give a complete proof of the theory of the dead time proposed above, a number of experiments were devised. They show that:

(*a*) Negative ions that reach the point obstruct or, if the ion current is sufficiently high, prevent the streamer formation.
(*b*) Negative ions are formed in a sufficiently large number in the streamer.
(*c*) The negative ions that are formed furthest from the point need a time to reach the point that is equal to the dead time, independent of the length of the streamer.

In this work all negatively charged particles that can appear in the gas, with the exception of electrons, are called negative ions.

(*a*) *Negative ions prevent the streamer formation*

The manner or place in which the negative ions are formed is, of course, of no importance. Accordingly the arrangement shown in Fig. 9 can be used to prove (*a*). If the point S is connected to a suitable posititve voltage V, streamers are formed as usual. The point A is placed 4–5 cm in front of the cylinder B. It is connected to a negative potential, so that a corona discharge can be obtained at the point. The point is tapered by grinding so that a current less than 10^{-7} amp can be obtained.

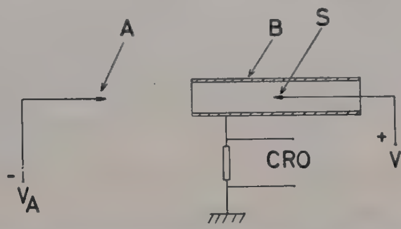

Fig. 9. An experiment in which negative ions and electrons formed at the negative point A reach the point S and prevent the streamer formation.

At first the voltage V_A is chosen just below the onset voltage, and no discharge appears at A. Streamers are in this case formed at S, as usual. If now the voltage V_A is increased so that a discharge starts at A, the streamer formation ceases at S and only the continuous discharge can be observed. By moving the point A in a direction normal to the axis of the cylinder, one can obtain a continuous transition between the two extreme cases just mentioned.

What essentially happens when a discharge burns at A is that negative ions and electrons move partly to the cylinder (probably most of them) and partly to the point S. However, it may be thought that it is not the negative charged particles that prevent the streamer formation, but the electrostatical influence of the point A on the field at S. But this seems very improbable, as the change of potential needed to start a discharge at point A is only about 100 volts. If the voltage of the point A is not close to the onset voltage, the discharge at point S is not affected by a much larger voltage change.

It may also be thought that the streamer formation could be prevented by the photons or excited atoms or molecules generated at the point A. But this also seems very improbable as the photons, exicted atoms and molecules generated at a positive point placed at a distance of only a few milimetres from the point at which the streamers are formed have no such influence on the streamer formation. This should be compared with the glowing-wire experiment described below.

From the experiment just described one can only conclude that negative ions and electrons with a current as low as 10^{-7} amp are able to prevent the streamer formation. The experiment shown in Fig. 10*a* was carried out in order to make a more accurate determination of the smallest current necessary to prevent the streamer formation. The point S and the plane P are the same as in Fig. 1. The diameter of the hole H is 8 mm. A thin platinum wire, G, has been placed opposite the hole at a distance of 3–4 cm from the plane. The wire can be heated by alternating current. When the wire is sufficiently warm electrons are emitted from its surface and a weak current of electrons and negative ions flows from the wire to the point. This current is measured with the galvanometer A. A large distance between the wire and the plane (3–4 cm) has been chosen because the current of positive ions reaching the wire must be much smaller than the electron current and the heating effect in the space around the point must be negligible. This heating effect is further diminished by means of an air current, as shown in the figure. The experiment was made in air at atmospheric pressure, room temperature and 75 % relative humidity. Currents as low as 10^{-10} amp could be measured with the galvanometer.

The voltage V was chosen so that streamers were formed at S; their formation was studied on the oscilloscope screen. If the temperature of the wire G was slowly increased, no change could be observed as long as the galvanometer did not indicate any current. However, as soon as a current could be measured with the galvanometer, the number of streamers formed per second decreased continuously as the current increased. When the current was 1×10^{-9} amp, the streamer formation had almost completely ceased.

A modification of the experiment just described was made in order to show

(1) that it must be negatively charged particles that prevent the streamer formation,
(2) that negative ions are able to prevent the streamer formation.

The experiment was made in air at atmospheric pressure and room temperature. The relative humidity was 75–100 %. The experimental arrangement is shown in Fig. 10*b*. In this case the diameter of the hole H in the plane P was 4 mm. Besides the plane P in Fig. 10*a* another plane F has been placed between the wire G and the point. The plane F is parallel to the plane P. The distance between the two planes is d. A hole (diameter 10 mm) has been drilled in the plane F, and thin wires have been stretched in the hole as a grid W. The distance between the grid and the wire G was about 2 mm.

The wire G was in this case heated by the current from a storage battery. The wire was connected to the plane F via a resistance R_1 and a battery B and to ground via the condenser C_1 and the resistance R_2. A direct current potential V_F was applied between the plane F and ground so that F acquired a negative potential. A variable frequency square-wave potential could be applied over the resistance R_2.

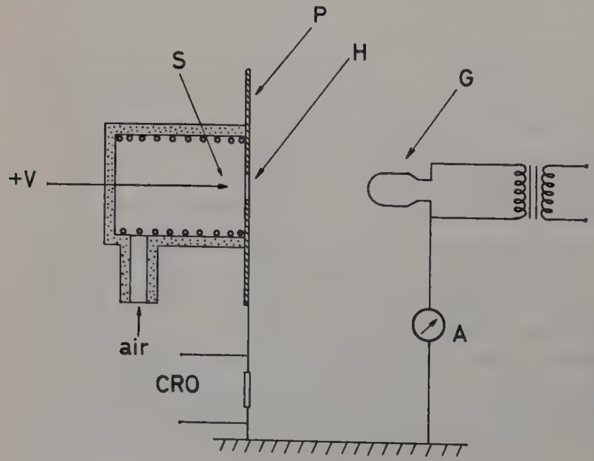

Fig. 10*a*. The arrangement used to show that a current of negative ions and electrons smaller than 10^{-9} amp is able to prevent the streamer formation. The electrons are emitted from the glowing wire G.

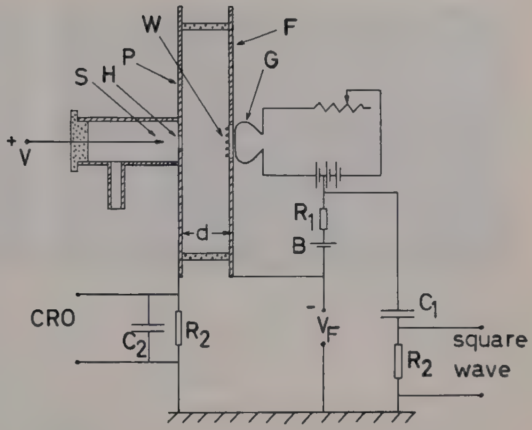

Fig. 10*b*. The arrangement used to measure the drift velocity of the slowest negatively charged particles that prevent the streamer formation. From this experiment it can be concluded that both electrons and negative ions are able to prevent the streamer formation.

In the following experiment no square wave potential was applied over R_2. A potential V_F of between 100 and 2000 volts was chosen. The connections to battery B were reversed, the wire G thus being charged to a negative potential of 10 volts compared to the plane F. A positive voltage was applied to the point so that streamers were formed at S. The streamer formation was then studied on the oscilloscope screen. The condenser C_2 does not affect the streamer formation in any way. It has been inserted only to make it easier to photograph the traces on the screen. The temperature of the wire was then slowly increased. When the temperature of the wire was sufficiently high, no streamers were formed at S. As in this case the wire G had a negative potential compared to the plane F, the electrons emitted from the wire could pass through the grid W to the point S. Of course many of the electrons attach themselves to atoms and molecules and from negative ions, but this only changes the mobility of the charges. If now the battery B is reversed so that the wire G acquires a positive potential (10 volts) compared to the plane F, streamers are formed at S in the same way as when the wire is not heated.

From this experiment it must be concluded that the streamer formation is prevented by negatively charged particles that reach the point. Positively charged particles are excluded because they have no chance of reaching the point. Nor could the thermionic effect of the wire, excited neutral particles or photons prevent the streamer formation because their influence must be independent of the voltage of the wire.

If a square wave alternating potential with sufficient amplitude is applied to the wire G, negatively charged particles can pass into the space between F and P only during the negative part of the cycle. By studying the streamer formation and the square wave signal applied to the wire G it is possible to measure the drift velocity of the negative charges that prevent the streamer formation. The picture on the oscilloscope screen is shown in Fig. 11*a*. The uppermost trace shows the square wave applied over R_2 and the other trace shows when streamers are formed. From the figure it is clear that after the potential of the wire G has become positive, a certain time T must elapse before streamers can be formed. This time must be equal to the drift time of the slowest negatively charged particles that prevent the streamer formation. It is also clear that after the potential of the wire has changed to negative, a certain time must elapse before the streamer formation ceases.

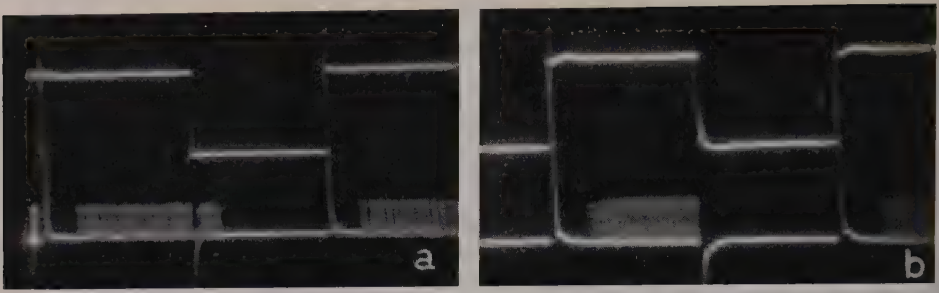

Fig. 11*a*. A photograph of the oscilloscope screen when a square wave potential is applied to the wire G (Fig. 10*b*). The uppermost trace shows the potential applied over the resistance R_2. The lower trace shows the streamer formation. Air at atmospheric pressure and 75–100 % relative humidity. $d = 14$ mm, 1 period = 0.01 sec.

Fig. 11*b*. The same as Fig. 11*a* but in this case $d = 0$. Notice the difference between *a* and *b* when the potential of the wire changes to negative. 1 period = 0.001 sec.

If the drift velocity of the negative charges is v in the space between the planes (Fig. 10*b*), the time needed for these charges to pass from the wire to the point can be written

$$T = T_1 + \frac{d}{v}\cdot$$

T_1 is the time needed for the particles to pass from the wire to the grid and from the plane P to the point. In the space between the planes we have a rather homogeneous field and we can therefore consider the velocity as a constant in this region. Let us suppose that we can write

$$v = k^- \cdot E = k^- \frac{V_F}{d},$$

where E is the field strength and k^- the mobility. Then we get

$$T = T_1 + \frac{d^2}{k^- \cdot V_F},$$

—that is, if k^- is a constant, T is a linear function of $1/V_F$.

The result of a measurement of T is given as a function of $1/V_F$ in Fig. 12. From the figure it is clear that k^- is not independent of the field strength. For values of E lower than 570 volts/cm, k^- equals 2.7 cm^2/volt · sec and for values of E in the region 570–1400 volts/cm, k^- equals 1.9 cm^2/volt · sec. As this mobility is about the same as the mobility of negative ions in oxygen and oxygen + nitrogen mixtures and about the same as the mobility of positive ions in nitrogen and oxygen, it can only be attributed to negative ions formed in the air [22, 23, 24]. Of course this does not mean that only negative ions are able to prevent the streamer formation. Electrons have the same effect but as the distance d is so great, most of the electrons that pass the grid attach to molecules, and form negative ions during their passage to the point.

If the distance d is small, the probability that the electrons will become attached to molecules and form negative ions during their passage to the point is much less than if d is large. An experiment was carried out in which d was made equal to zero (Fig. 11*b*). The square wave voltage was applied to the wire G in the same way as

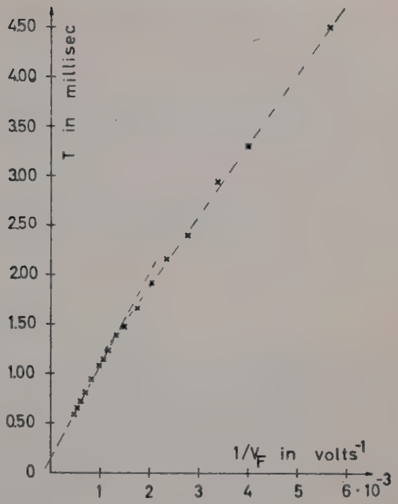

Fig. 12. The drift time T of the negative ions as a function of $1/V_F$. The measurement has been made with the experimental arrangement shown in Fig. 10*b*. $d = 14$ mm. Air at atmospheric pressure, room temperature, 75–100 % relative humidity. The mobility, k^-, is 2.7 cm²/V · sec for low values of V_F and 1.9 cm²/V · sec for higher values of V_F.

described above. After the potential of the wire had changed to positive, there was no fundamental difference compared to the case shown in Fig. 11*a*. The only difference was that the time T was much shorter (of the order of 10^{-4} sec). On the other hand after the potential of the wire had changed to negative, the picture on the oscilloscope screen differed from that in Fig. 11*a*. As soon as the potential of the wire had changed to negative the streamer formation ceased. As the negative ions cannot reach the point in a few microseconds, it must be electrons that prevent the streamer formation just after the voltage of the wire has changed to negative.

When oxygen, instead of air, was introduced in the corona gap, the streamer formation did not cease as soon as the potential of the wire G became negative. This is to be expected as the attachment probability is much greater in oxygen than in air [25]. The figure on the oscilloscope screen was like that in Fig. 11*a*.

As it can be supposed that in the experiment shown in Fig. 10*a* some of the electrons and negative ions did not reach the point, the value 1×10^{-9} amp is an upper limit for the electron and negative ion current that is necessary to prevent the streamer formation. By measuring electrostatically the decline of the potential of the point when the connection to the high tension source was broken, it was found that the negative ion and electron current to the point must be about 2×10^{-10} amp when almost no streamers are formed.

It is of interest to compare the results of these experiments with an observation made by Kip [4]. He used a radioactive source to ionize the air in the corona gap. Generally streamers were formed if the point voltage was just below onset. However, if a very strong radioactive source was used, the streamer propagation ceased. In this experiment, as in those described above, the essential thing is that negative ions and electrons formed by an auxiliary ion source reach the point.

(*b*) *Negative ions are formed in the streamer*

Every time an electron collides with a gas molecule there is a certain probability that it will become attached to the molecule and form a negative ion. Negative ions are formed in all gases used in this work with the exception of N_2 and A, where no negative ions have been found [18]. When a streamer is formed, electrons are produced in the streamer; the number per centimeter of length seems to be approximately constant—that is, independent of the distance to the point. According to Amin's measurements [12] this number is 8×10^9 electrons/cm. In the discharge used in this investigation only about 3×10^9 electrons are produced per centimeter.

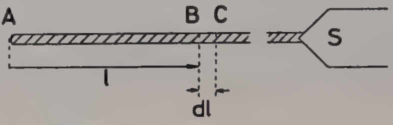

Fig. 13. Figure for the derivation of Eq. (5).

The number of negative ions produced per centimeter by attachment of electrons to gas molecules can be determined in the following way. Suppose that the streamer tip has reached A (Fig. 13) but cannot propagate any further. In Fig. 13, l is the distance from the tip of the streamer to some point B of the streamer. Immediately after the electrons are produced they begin to move to the point. Suppose that in all n_l electrons enter the space B–C at B and that n_{l+dl} electrons leave it at C. The number of collisions between an electron and the gas molecules when the electron moves from B to C is proportional to dl. Hence, the number of negative ions formed in B–C can be written $n_l \cdot \eta \cdot dl$, where η is the attachment coefficient. If n_0 is the number of electrons produced per centimeter when the streamer is formed, it follows that

$$n_{l+dl} = n_l - n_l \cdot \eta \cdot dl + n_0 \cdot dl$$

or

$$\frac{dn_l}{dl} + \eta n_l = n_0.$$

As $n_l = 0$, if $l = 0$, the solution of this equation is

$$n_- = \eta \cdot n_l = n_0 (1 - e^{-\eta \cdot l}), \tag{5}$$

where n_- is the number of negative ions per centimeter just after the streamer has been formed. η has been considered as a constant.

It has been assumed that the time during which the negative ions are formed is short compared with the time that the negative ions need to reach the point. This is justifiable because the mobility of the electrons is about 100 times as great as the mobility of the ions [21].

It is easy to prove that $\eta > h/\lambda$, where h is the attachment probability and λ is the mean free path of the electrons. When an electron moves a distance dl it collides at least dl/λ times with the gas molecules because its path is zigzagged. Consequently the probability that it becomes attached is $\eta \cdot dl > (h/\lambda) dl$. The value of h is different for different gases and varies with E/p, where E is the field strength and p the pressure. It is rather small for dry air but is not less than 1×10^{-6} [18, 25]. The mean free path of electrons in air at atmospheric pressure is about 4×10^{-5} cm [19]. With this value one obtains $\eta = 2.5 \times 10^{-2}$ cm^{-1}. With $n_0 = 3 \times 10^9$ electrons/cm

$$n_- = 3 \times 10^9 (1 - e^{-2.5 \times 10^{-2} \times l}) \text{ cm}^{-1}$$

or for small values of l $\quad n_- = 7.5 \times 10^7 \times l \text{ cm}^{-1}$.

The current caused by the movement of the negative ions is

$$I_- = n_- \cdot v \cdot e,$$

where v is the drift velocity of the negative ions and e is the electronic charge, 1.6×10^{-19} coulombs. But the drift velocity is proportional to the field strength—that is, $v = k^- \cdot E$, where k^- is the mobility. The mobility in air is about 2 cm²/V·sec at atmospheric pressure [20, 21, 24]. The field strength necessary for the propagation of the streamer at atmospheric pressure is at least 3.0 kV/cm (see below). Using this value of E one obtains $v = 6 \times 10^3$ cm/sec. It is now possible to determine the value of l at which $I_- = 10^{-9}$ amp. This is $l = 0.014$ cm.

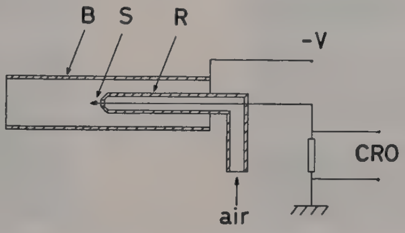

Fig. 14. Arrangement used to show that negative ions are formed in the streamer.

This means that at a distance of 0.14 mm from the streamer tip there is a current of negative ions that is sufficient to prevent the streamer formation. This value of l is indicated by an arrow in Fig. 3. As is clear from equation (5), n_- increases with increasing l, and consequently I_- increases as well. In the above calculation the numerical values have been chosen so that the value of l obtained is a maximum. Thus $h = 10^{-6}$ is a minimum value for dry air and h is probably much larger if the air contains water vapour. Cravath found that h increased greatly if both oxygen and water molecules were present [26]. Now it has been shown theoretically that the number of negative ions formed in the streamer is sufficient for preventing the streamer formation.

The following experiment was made in order to prove experimentally that negative ions are formed in the streamer (Fig. 14). In this case a cylinder, B, is used as the negative electrode. The point S has been placed just outside the end of the tube R, through which air can be blown.

The voltage V is chosen so that streamers are formed at S, and the shape of the voltage pulses is studied on the oscilloscope screen. If the air current through the tube is very slow, a pulse shape shown in Fig. 15a is obtained. The total sweep time is about 300 μsec. When the streamer is formed, the voltage falls very rapidly to a value that lies outside the figure. Then it rises, at first rapidly but later slowly. The slowly rising part of the curve can be caused either by positive ions moving from the point or by negative ions that reach the point. If it is caused by the positive ions, the voltage pulse would become shorter if the rate of flow of the air is increased. If it is caused by the negative ions, it would be longer for these ions move in a direction opposite to the air current. In Figs. 15b, c and d the air current has been successively increased, and one sees how the voltage requires a progressively longer time to reach the starting value. Consequently the positive ions must play a secondary role, and the slowly rising potential must be caused by the negative ions. One cannot estimate the

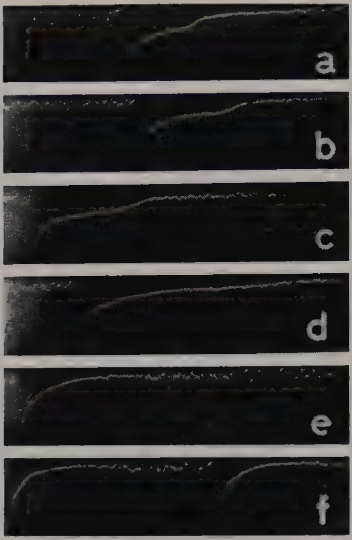

Fig. 15. The shape of the streamer pulses at different velocities of the air current through the tube R (Fig. 14). 30 % relative humidity. The slowly rising part of the trace must be caused by negative ions and not by positive ones. The sweep speed is the same in all the figures *a–f*. The total sweep time is about 300 μsec.

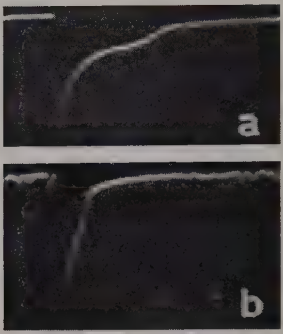

Fig. 16. The shape of the streamer pulse. Air at atmospheric pressure at *a* 30 % and *b* 100 % relative humidity. The sweep speed is the same in both cases.

number of negative ions, because the ions split into electrons and molecules in front of the point [27]; the electrons ionize and increase the current. If the air current is very fast, the ions formed furthest from the point are completely blown away, which is clear from Figs. 15*e*, *f*.

As is shown in Fig. 3, the streamers are much longer at 30 % relative humidity than at 100 %. Fig. 16*a* shows the voltage pulse in the former case and Fig. 16*b* in the latter. The slowly rising part is much longer at 30 % than at 100 %. This is in good agreement with the assumption made above. The positive ions would hardly be able to cause such a large difference.

(*c*) *The dead time is equal to the drift time of the negative ions*

As the field strength between the point and the plane is very difficult to calculate, it is impossible to make a direct calculation of the drift time of the negative ions. With the arrangement shown in Fig. 17, however, it is possible to attain a uniform field for the propagation of the streamers. A plane Q is placed parallel to the plane P at a distance d from it. The three electrodes, S, P, and Q, are fitted in a cylindrical container made of perspex. The plane Q is supported by a metal rod Z, the outer end of which is threaded. The distance d can be changed by turning the rod.

If the distance between the point S and the plane P is about the same as the length of the streamers and if the field strenght in the space between the planes is sufficiently high, the streamers pass through the hole, H, and do not stop until they reach the plane Q. Streamers of different length can be obtained by varying d. The field strength

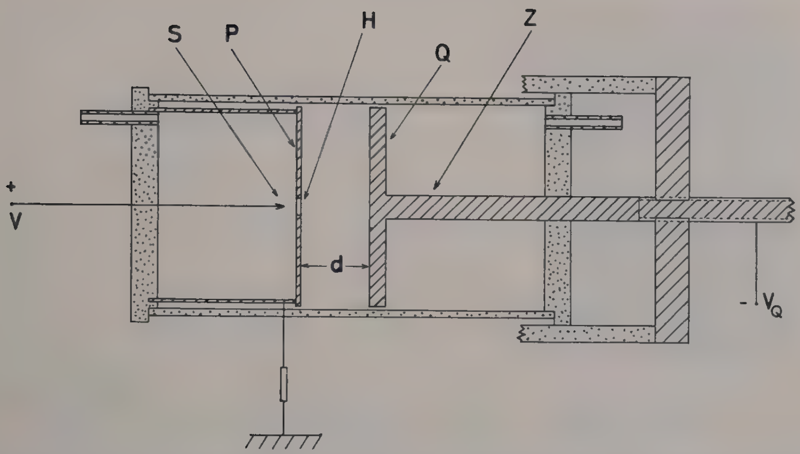

Fig. 17. The arrangement used for the measurement of the dead time as a function of the streamer length. The streamers are formed at S, pass through the hole H and reach the plane Q. The distance d can be varied by turning the threaded rod.

E necessary for the propagation of the streamers has been found to be independent of the distance d. Since the field is not uniform in the neighbourhood of the hole, the field strength E must be determined by plotting V_Q, the voltage difference, between the two planes P and Q, as a function of d. The resulting curve is a straight line, the slope of which is equal to the field strength. This field strength is generally much lower than that necessary for breakdown. Thus for air at atmospheric pressure the necessary field strength is about 5 kV/cm while that necessary for breakdown is 20–30 kV/cm.

If the field strength in the space between the planes is increased from zero it finally reaches a value E' at which some of the streamers reach the plane Q. If all the streamers are to reach the plane, a somewhat higher value $E' + \Delta E' = E''$ is needed. When the streamers do not cross the gap, the general shape of their time distribution curve is given by Fig. 7. When the field strength between the planes P and Q is so high that all the streamers reach the plane Q, a striking change is observed in the time distribution of the streamers (cf. Fig. 20). The streamers are very regularly distributed in time, which means that in Eq. (4) $t_1 \to t_0$ and $k \to \infty$. If we put $t_1 = t_0$ and $k = \infty$ in Eq. (4), we get $t_0 = 1/n$. Consequently in this case we can obtain the dead time t_0 in a simple way by measuring the total number, n, of streamers formed per second.

In Fig. 18 the measured dead time is plotted as a function of d. The measurement has been made in air at atmospheric pressure and 75 % relative humidity. The field strength E'' necessary for the streamer propagation is in this case 5.7 kV/cm. The crosses are the measured values. As is clear from the figure, the dead time t_0 is a linear function of d—that is, t_0 is a linear function of the streamer length. We have supposed that the dead time is caused by the negative ions. The drift velocity of these ions is then equal to the slope of the line. The mobility of the ions, k^-, is determined from the equation $v = k^- \cdot E''$, and one obtains $k^- = 0.91$ cm²/V·sec. This value is smaller than that measured above (Fig. 12). However, this is quite natural, as will be clear below.

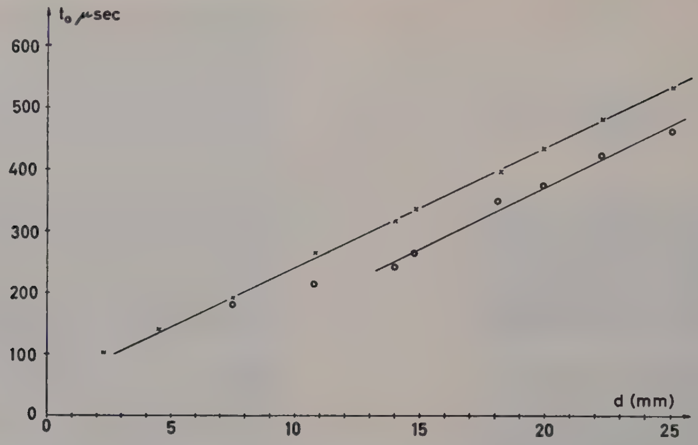

Fig. 18. The dead time t_0 as a function of the streamer length. The crosses are the values measured when the streamers reach the plane Q. The rings are the values maesured when a hole (diameter = 8 mm) had been drilled in the plane Q so that the streamers did not reach the metal surface.

When the streamer reaches the plane Q, a large number of electrons are emitted from it, probably mostly by the photoelectric effect. Of course these electrons form negative ions in the same way as those produced in the streamer. Doehring [28] has calculated the current to the positive electrode when electrons are liberated from the cathode during a short time. When the electrons and negative ions reach the point, it is to be expected that its potential will vary as shown in Fig. 19. The pulse to the left in the figure is caused by the electrons and the "tail" by the negative ions. If all the negative ions moved with the same velocity, the potential would vary according to the dashed curve. But this is not the case; the real potential variation is shown by the continuous curve. The shape of the voltage pulse is shown in Fig. 20. It must be emphasized that in this case the high pulse to the left is not caused by the electrons emitted from the plane Q but by the electrons produced in the streamer. The distance d is so great and the gas pressure so high that almost all electrons emitted from the plane are attached to the gas molecules.

In order to prevent the streamers from reaching the plane Q, an 8 mm diameter hole was drilled in it opposite to the point. The streamers then propagated in the space between the planes as before, but as they ended in the air very few electrons were emitted from the plane. The measurements are in this case somewhat less accurate than in the case above. This is partly because the field is not uniform, especially for small values of d, and partly because all streamers are not of exactly the same length. The field strength in front of the hole of the plane Q decreases comparatively slowly, and consequently some streamers can advance somewhat further than others. Only the longest streamers are visible, but the dead time is measured for the shortest ones. The result of this measurement is shown in Fig. 18. The measured values are marked with circles. For d greater than 13 mm they lie on a straight line. If d is large, the hole in the plane Q does not affect the field strength so much as if d is small—that is, the field is more uniform in the former case than in the latter. The measured values of the dead time are smaller than for the non-perforated plane (Q). The reason for this is probably that the dead time is measured for the shortest

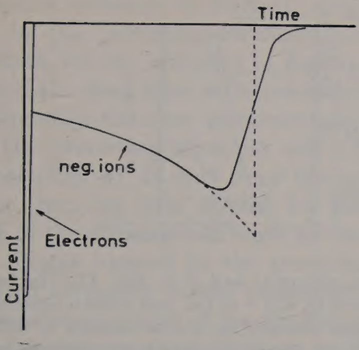

Fig. 19. The potential variation of the positive electrode when electrons are emitted from the cathode during a very short time and negative ions are formed in the gas. This curve is taken from Doehring [28]. The dashed curve shows the ideal case when all ions move with the same velocity. The full curve is to be expected as a consequence of diffusion effects.

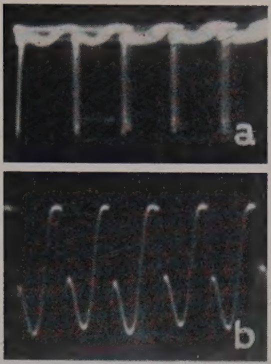

Fig. 20. The potential variation of the point when the streamers reach the plane Q. *a*, "Low" amplification and many sweeps. *b*, "High" amplification and one sweep. In this case we see only the pulse caused by the arrival of the negative ions at the point. Air at atmospheric pressure and 100 % relative humidity.

streamers while the value of d used corresponds to the longest ones. As the lines in Fig. 18 are almost parallel, a determination of the mobility of the ions gives about the same value as was obtained above.

Now one may ask why the mobility of the negative ions determined from Fig. 18 is so low compared with the values determined from Fig. 12. This is quite natural: we know that the streamer formation at the point is prevented if a current of negative ions greater than about 2×10^{-10} amp flows to the point. This is the case in the experiment shown in Fig. 10*b*, for the current has been so adjusted that it is only slightly greater than this value. In the experiment described on page 417 the electrons liberated from the plane Q gives rise to a much greater current of negative ions. The charge produced per centimeter of the streamer is about 5×10^{-10} coulombs and the charge emitted from the plane Q must be of this order of magnitude as well, otherwise it would not be possible to observe the hump caused by the negative ions, Fig. 20.

If we suppose that a charge q of electrons is emitted by the plane Q (Fig. 17) at the time $t = 0$, these electrons will either form negative ions or reach the plane P or the point in a few microseconds. The space charge of negative ions caused by these electrons is given by

$$q^- = q \cdot \eta \cdot e^{-\eta \cdot x},$$

where η is the attachment coefficient and x the distance from the plane Q (Fig. 21). In Fig. 21 $q = 1 \times 10^{-10}$ coulombs and $\eta = 1.0$ cm^{-1}, which is the order of magnitude of η for air at atmospheric pressure and 100 % relative humidity. The space charge giving rise to a current of 1×10^{-9} amp is about 10^{-13} coulombs/cm if the field strength is 5 kV/cm and the mobility $k^- = 2.0$ cm^2/V·sec. The value 10^{-13} coulombs/cm is indicated in Fig. 21. From these considerations it is clear that the current of negative ions caused by the emission of electrons from the plane Q is about 10^3 times greater than that necessary to prevent the streamer formation. In view of this situation it is not surprising that the mobility determined from Fig. 18 is lower than

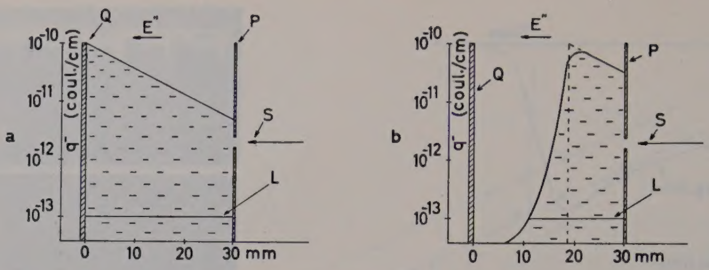

Fig. 21. The space charge of negative ions between the planes Q and P in Fig. 17. The ions are formed by attachment of electrons emitted from the plane Q. *a*, $t = 0$, i.e. just after a streamer has been formed. *b*, $t = 200$ μsec. The shape of the curve has changed as a consequence of diffusion, cluster formation, etc. The smallest space charge that gives rise to a current sufficient to prevent the streamer formation is shown by the line L. $q = 10^{-10}$ coulombs. $\eta = 1.0$ cm^{-1}.

that determined from Fig. 12. There are several effects that cause some of the ions to move more slowly than the majority of them. Such effects are diffusion, cluster formation and the influence of the positive ions moving in the opposite direction. It is to be expected that about 200 μsec after the appearance of a streamer the space charge is something like that indicated in Fig. 21*b*.

In the experiment shown in Fig. 10*b* the effect of the diffusion, cluster formation and the positive space charge on the measured values of the mobility is probably rather small. Therefore this experiment indicates a new method for measuring the drift velocity of negative ions at high pressures. Of course the arrangement in Fig. 10*b* has certain disadvantages. The hot wire increases the temperature of the gas but this electron source can be replaced by a more suitable one. The use of a corona discharge (negative point) would be a good improvement. Of course a necessary condition for the use of this method for measuring the mobility is that streamers are formed in the gas under investigation. However, as soon as streamers are formed this method can probably be used.

6. Discussion

From the investigation above it must be concluded that the negative ions formed in the streamer are responsible for the dead time, at least if the streamers are long. All experimental facts concerning the dead time can be explained in a simple way in terms of the negative ions. However, this does not exclude the posssibility that the dead time can be caused by other processes, for instance by the positive space charge. Yet, if the streamers are long, these processes can hardly be of any importance. Thus such a process is to be expected only if the streamers are short—that is, if the dead time is short. But it has always been observed that the shorter the streamer is, the shorter the dead time. If the positive ions caused the dead time, one would expect the dead time to have a lower limit and that it would be rather independent of the length of the streamer. If such a limit exists, it is less than 10^{-6} sec. This dead time has been observed in a $N_2 + CCl_4$ mixture; of course, the streamers are very short. Thus, the positive space charge from the preceding streamer permits a dead time as short as 1 μsec.

When a streamer is formed, almost all the positive ions formed nearest to the point in the preceding streamer have moved a distance that is longer than the streamers, for the mobility of positive ions is about the same as that of the negative ions and the dead time is determined by the negative ions having the lowest mobility. Consequently the new streamer will not be deflected by the positive space charge from the preceding streamer and all streamers are able to propagate in the same channel (Fig. 3). If only very few negative ions are formed, the dead time will be shorter than the time needed for the negative ions to move a distance equal to the length of the streamers. This is a consequence of Eq. (5). This means that the positive space charge formed by the preceding streamer has not left the space in which the following streamer would propagate. The streamer will therefore be deflected and the visual appearance of the discharge differs from that shown in Fig. 3. The streamers propagate only a short distance in the direction of the point and are then deflected to the sides. This is the case if a mixture of nitrogen and argon is used (commercial nitrogen containing small amounts of oxygen).

As we know that a space charge of negative ions of about 10^{-13} coulombs/cm is sufficient to prevent the streamer formation, we can calculate the maximum value of η for which the negative ions have no influence on the dead time. This value of η is obtained if we substitute $n_- = 10^{-13}/1.6 \times 10^{-19}$, $n_0 = 5 \times 10^{-10}/1.6 \times 10^{-19}$ and l (the length of the streamers) $= 1$ cm in Eq. (5). The value of η obtained in this way is 2×10^{-4} cm^{-1}. This is clearly a very low value since it is the value of η for oxygen at a pressure of about 2×10^{-3} mm Hg. Consequently the admixture of a very small amount of a gas that forms negative ions is sufficient for the appearance of a dead time.

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